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Factors affecting workpiece surface integrity in slotting of CFRP

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Abstract

CFRP use in aerospace applications has seen a dramatic increase over the last decade. The slotting/routing process is used to trim excess material from cured CFRP panels in wing manufacture. The work presented details the effect of different slotting parameters, tool materials (WC & PCD) and cutting environment (chilled air & dry) on the surface roughness and integrity of machined CFRP laminates when employing an L16 fractional factorial Taguchi experiment. Scanning electron micrographs and 3D topographic maps show the influence of fibre orientation with respect to the cutting direction. Thermal damage (burning & resin melt) were minimised using chilled air. Use of PCD tooling provided significantly increased productivity compared to coated WC with workpiece surface roughness of $\sim 3.6\mu\text{m Sa}$ at 200m/min cutting speed and 0.03mm/tooth feed rate.

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Keywords: Composite, Diamond, Surface integrity

1. Introduction

Carbon fibre reinforced plastic (CFRP) composites are increasingly being used for a wide range of applications in the automotive and aerospace industries, owing to their superior physical/mechanical properties relative to weight over traditional materials such as steel and aluminium (CFRP is $\sim 70\%$ and 40% lighter respectively) while being only $\sim 20\%$ more expensive [1]. Aircraft including the Airbus 380 and A350 XWB incorporate approximately 25% and 53% (wt) of CFRP respectively within their

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fuselage, wing and empennage assemblies. In addition to providing a stronger/stiffer structure, the weight savings accrued by employing CFRP translates into more fuel efficient and environmentally friendly airplanes. While components made from CFRP are normally cured to near-net-shape, machining operations such as slotting, routing or edge trimming, are still required to remove excess material, produce complex contours and meet product dimensional tolerances as well as quality requirements [2]. Research involving milling/routing has been on-going for over 20 years. Work in the early 1990's by Hocheng et al. [2] showed that there was a relationship between the cutting mechanisms (buckling, bending or shear depending on fibre orientation with respect to machining direction) and resulting surface roughness, when milling unidirectional CFRP. They found that best results were obtained when fibres were parallel (0°) to the tool feed. Ramulu et al. [3] recommended that 3D roughness parameters (S_a , S_t , etc.) were preferable for characterising machined CFRP surfaces as equivalent 2D measures such as R_a and R_t were not sufficiently discriminating. In addition, it has been suggested that assessment of several parameters are necessary in order to provide a comprehensive description of a surface [4]. Previous studies have also found that high cutting speeds in tandem with low feed rates generally resulted in improved surface quality when edge milling due to the lower amount of mechanical/thermal damage induced [5, 6]. The present work aims to study the effect of operating parameters, tool materials and cutting environment on resulting workpiece surface roughness and integrity following slotting of CFRP.

2. Experimental work and procedures

Autoclave cured CFRP laminates produced by manual lay-up of unidirectional (UD) prepregs (0.26mm thick), consisting of intermediate modulus (294 GPa) carbon fibres held within an epoxy resin matrix, were used for all tests. The material designation TORAY 3911/34%/UD268/T800SC-24K indicates the resin type, resin content by weight%, fibre areal weight (g/m^2) and fibre type respectively. Each plate was made up of 40 plies and stacked according to the sequence $[(45^\circ, 0^\circ, 135^\circ, 90^\circ)_5]_{s40}$ giving final dimensions of $600 \times 550 \times 10.4$ mm. The cured laminates were then sectioned into 2 different sized specimens of 100×100 mm for force measurement and slot integrity evaluation and 260×240 mm for tool life analysis. Four different cutting tool materials were investigated involving DLC (diamond like carbon) coated carbide benchmarked against coarse (CTM-302), medium (CTB-010), and fine (CMX-850) grained polycrystalline diamond (PCD) grades. The average grain sizes for the different PCD materials were 13.8, 6.8 and $1.3 \mu\text{m}$ respectively. All end mill cutters were 12mm in diameter with two straight flutes and a 0° rake angle. A modified Taguchi fractional factorial design (L16 orthogonal array) comprising 16 runs was employed (see Table 1), in order to minimise the number of tests compared to a full factorial configuration, which would have entailed 128 trials, not including replications. The axial depth of cut was kept constant at 5mm. Experiments were carried out on a 3-axis Matsuura FX 5 CNC machining centre with a maximum spindle speed of 20,000rpm at 15kW. The machine was equipped with a Filtermist dust extraction system capable of removing particles down to $0.3 \mu\text{m}$, and a NexFlow vortex tube cooling system (type 56030FD). This was installed with dual nozzles directed at the cutting zone to supply chilled air at 8°C and 0.4bar output pressure. Cutting forces were measured with the test coupon mounted on a Kistler 9257 platform dynamometer (linked to charge amplifiers) using a specially designed jig, see Fig 1a. CFRP plates for tool life trials were held using a VacMagic-VM300 vacuum fixture to avoid use of clamps and maximise cut length. In order to preserve workpiece material, a 3/4 engagement procedure as opposed to complete slotting was adopted for the tool life tests, see Fig 1b. At regular intervals of cut length, a full slot was machined to enable measurement of force and associated tool wear with the test coupon kept for subsequent integrity analysis. The tool life criterion was either a cut length of 28,000mm or a maximum flank wear of 0.3mm. Micrographs of the machined surfaces were taken using an optical microscope and a JEOL 6060 scanning electron microscope (SEM), while 2D and 3D

surface roughness measurements (transverse direction)/topography plots were obtained using a Talysurf 120L contact stylus surface roughness tester, see Fig 1c. Three 2D readings were taken for each surface over an evaluation length of 2.4mm (0.8mm cut-off) at regular intervals and averaged, while for 3D plots (evaluation area of 2.4mm x 1.5mm), one measurement was recorded for each slot after the first pass (new tool) and at the last slot for selected trials (Tests 11 & 15). Statistical analysis involving main effects plots and analysis of variance (ANOVA) was used to identify significant factors/levels with respect to response measures and associated percentage contribution ratios (PCR) calculated. All analysis was performed on the down milled side only as this was the surface of interest for the application envisaged.

Table 1. L16 orthogonal array (OA)

Test	Cutting speed (m/min)	Feed (mm/tooth)	Tool material	Cutting environment
1	200	0.15	DLC coated WC	Chilled air
2	350	0.10	DLC coated WC	Chilled air
3	500	0.06	DLC coated WC	Dry
4	650	0.03	DLC coated WC	Dry
5	200	0.10	CTM-302 PCD	Dry
6	350	0.15	CTM-302 PCD	Dry
7	500	0.03	CTM-302 PCD	Chilled air
8	650	0.06	CTM-302 PCD	Chilled air
9	200	0.06	CTB-010 PCD	Chilled air
10	350	0.03	CTB-010 PCD	Chilled air
11	500	0.15	CTB-010 PCD	Dry
12	650	0.10	CTB-010 PCD	Dry
13	200	0.03	CMX-850 PCD	Dry
14	350	0.06	CMX-850 PCD	Dry
15	500	0.10	CMX-850 PCD	Chilled air
16	650	0.15	CMX-850 PCD	Chilled air

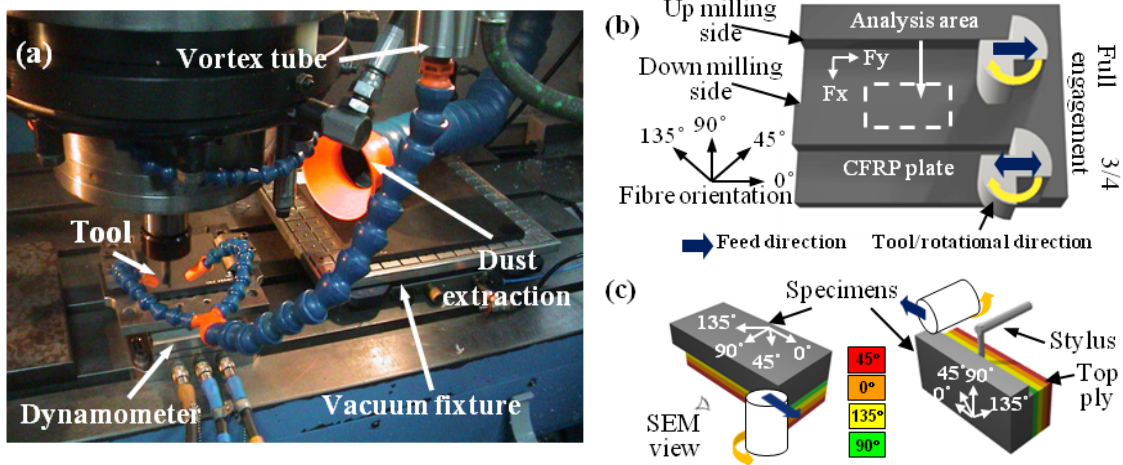


Fig. 1. (a) Experimental setup; (b) full vs. 3/4 tool engagement; (c) cutting/feed direction with respect to fibre orientation

3. Results and discussion

3.1. Tool material

DLC coated end mills showed extremely poor wear resistance compared to the PCD tools irrespective of operating conditions. Tool life did not exceed 900mm cut length (Test 1) for 0.3mm flank wear. The high levels of tool wear resulted in adverse workpiece surface roughness, which was up to $17.9\mu\text{m}$ Sa following only 100mm cut length (flank wear $>0.3\text{mm}$) in Test 4, see Fig 2a. Conversely, PCD tools showed significantly longer tool lives due to their superior abrasion resistance, in contrast to results reported by Lopez de Lecalle et al. [7]. The majority of tools achieved a cut length of 28,000mm without exceeding a flank wear of 0.18mm, with the exception of Tests 5, 6, 13 & 16. Larger amounts of chipping were evident when employing the CTM-302 grade, particularly at low cutting speed/high feed rate combinations (Tests 5 and 6). This was most likely due to its bigger grain size and lower resistance to impact loads typical of milling operations. In terms of tool life, the CTB-010 showed the lowest level of flank wear ($\sim 0.1\text{mm}$) after 28,000mm length cut when operating at 500m/min cutting speed and 0.15mm/tooth feed rate under dry conditions (Test 11). This was attributed to its favourable balance of hardness and thermal properties. The best surface roughness produced using PCD end mills was with the CMX-850 grade where an Ra/Sa of $3.60\mu\text{m}/3.65\mu\text{m}$ was obtained with a new tool (Test 13), although this test had to be stopped after 16,400mm cut length (flank wear $\sim 0.13\text{mm}$) due to burning of the workpiece. This was similar to the $3.2\mu\text{m}$ Ra typically required for aerospace applications [8] and probably the result of the superior tool edge finish achievable with ultra fine grained PCD material. Results from Test 15 using the CMX-850 tool also showed a relatively low surface roughness with a Sa value of $\sim 5.7\mu\text{m}$ even after 28,000mm cut length, although evidence of fibre pullout was observed at the 90° ply, see Fig 2b. Despite this, the cutting force (F_x) at this point was only 600N, which was about 50% of that seen with equivalent DLC tools. While the main effects plot highlighted CTM-302 PCD as preferable for lowest surface roughness (measured in terms of Ra at 0.1mm flank wear level), associated ANOVA results showed that tool material was not a statistically significant factor, with a relatively low PCR of 5.44%.

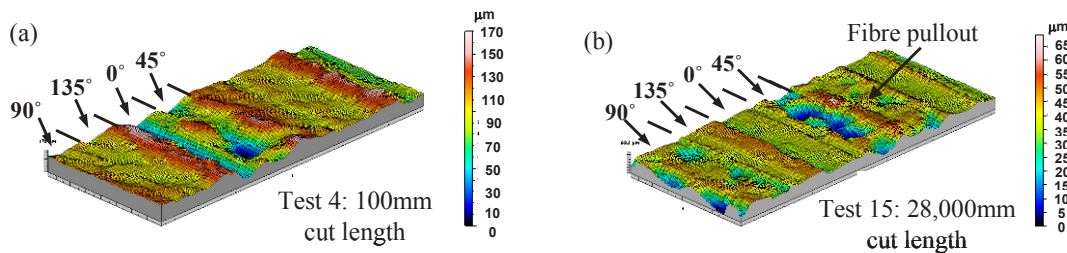


Fig. 2. 3D topography maps of surfaces machined with; (a) DLC coated WC - Test 4; (b) CMX-850 PCD - Test 15

3.2. Cutting speed/feed rate combinations and cutting environment

While high cutting speeds and low feed rates are recommended for edge trimming CFRP, the situation is somewhat different in slot milling where the low thermal conductivity of the resin matrix tends to retain the heat within the cutting zone. This leads to softening, degradation and burning of the matrix material that binds fibres together [4]. The softened matrix allows flexible fibres to 'escape' from the cutting edge and spread over a wider area, especially those in the 90° and 135° direction. This was observed in trials at low levels of feed rate and cutting speed (Test 13) where disintegration of the matrix also resulted in the

loss of fibres particularly in the 0° direction, see Fig 3a and 3b which shows the difference in surfaces produced with new and worn tools. Operating without chilled air was thought to be a further contributory factor as burning of the workpiece generated an acrid odour, suggesting that the glass transition temperature of the resin (180°C) was exceeded. Increasing cutting speed and feed rate in Test 15 with chilled air led to significantly improved surfaces, due to the absence of thermal damage, see Fig 3c. The main effects plot showed that low cutting speed with high feed rate was the best combination for minimum surface roughness, as this most likely reduced cutting temperatures as well as the total contact time between the tool and workpiece. In terms of ANOVA results, feed rate was the only statistically significant variable affecting surface roughness with a 57.5% contribution. While the use of chilled air improved the removal of dust particles from the slot and helped reduce the incidence of matrix burning/sticking, the corresponding ANOVA showed that cutting environment was not statistically significant with respect to workpiece surface roughness together with a negligible PCR.

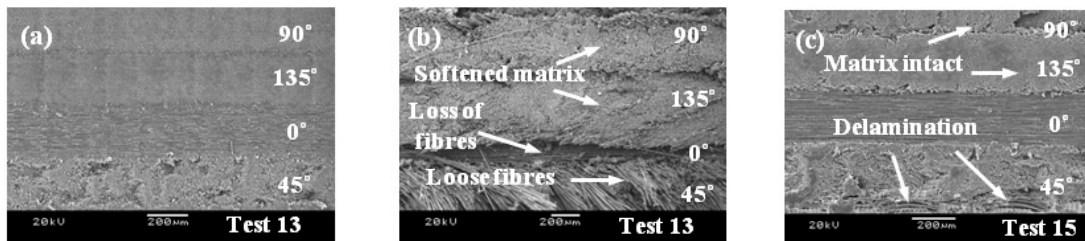


Fig. 3. SEM micrographs; (a) Test 13 new tool; (b) Test 13 worn tool (16,400mm); (c) Test 15 worn tool (28,000mm)

3.3. Fibre orientation

Plyes oriented at 45° suffered severe damage where fibres were generally bent and ‘lifted-up’ as the cutting edge advanced, which can subsequently cause splitting/interfacial failure of fibre bundles and the matrix. Some of these fibres then proceeded to fracture/were pulled out while others were merely flexed, thereby producing a wavy surface, see Fig 4a. High cutting forces (when tool worn) and matrix softening can also result in reorientation of 45° fibres as shown in Fig 4b, and surface delamination of the unsupported top ply as shown in Fig 3c.

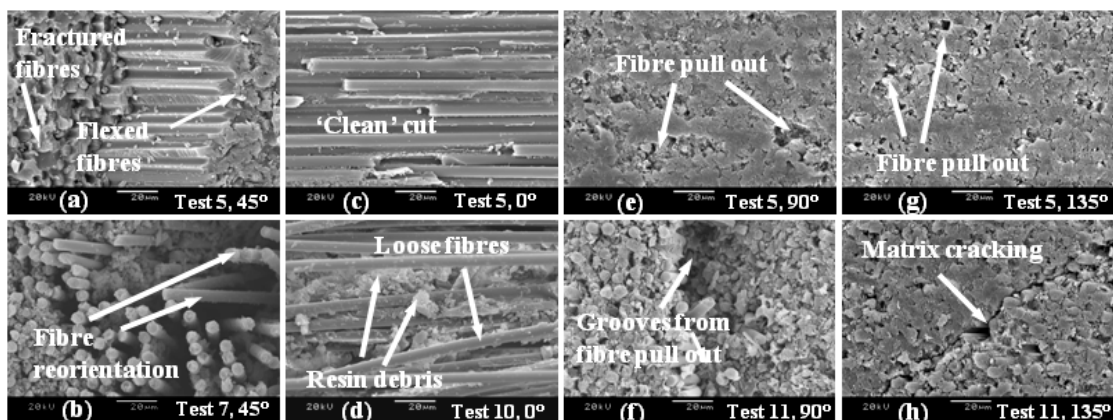


Fig. 4. Damage at different fibre orientations; (a-b) 45°; (c-d) 0°; (e-f) 90°; (g-h) 135°

Surfaces with fibres at 0° generally showed the least damage, see Fig 4c, with fibres removed cleanly as a result of fracture by buckling [9]. These however were responsible for high cutting forces as they become orientated at 90° with respect to the cutting edge at the point of maximum chip thickness (middle of slot), which can cause loose fibres to form, see Fig 4d. Fibre pull out was observed in 90 and 135° plies leading to empty holes or large grooves (Figs 4e-g) as fibres tended to break at locations beneath the machined surface/depth of cut [10]. Matrix cracking as a result of elevated forces at high feed rates was also seen as shown in Fig 4h.

4. Conclusions

All the DLC coated carbide end mills tested wore rapidly while the majority of the PCD tools achieved 28,000mm cut length without exceeding 0.3mm flank wear (estimated up to ~95 times longer tool life). Burning of the CFRP resin was seen in some of the trials, particularly when cutting dry and employing low feed rates. Statistical analysis showed that the combination of low cutting speed and high feed rate is recommended in terms of improving surface roughness, with feed rate being a significant factor having a PCR of 57.5%. Application of chilled air generally prevented burning due to better evacuation of workpiece debris and cooling, despite cutting environment not being a statistically significant factor affecting surface roughness. Wavy surfaces were observed at 45° orientated plies while those in the 90° and 135° direction suffered matrix cracking and fibre pull out due to high cutting forces and softening of the resin. In general, the best surface was found on plies where the fibres were parallel to the tool feed/cutting direction (0°).

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